Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Journal of Empirical Finance 12 (2005) 353–373
Journal of EMPIRICAL FINANCE
www.elsevier.com/locate/econbase

Index futures arbitrage before and after the introduction of sixteenths on the NYSE

Thomas Henker[a,*], Martin Martens[b]

[a] *University of New South Wales, Faculty of Commerce and Economics, School of Banking and Finance, Quadrangle Building, UNSW 2052, Sydney, Australia*
[b] *Erasmus University, Rotterdam, The Netherlands*

Accepted 1 April 2004
Available online 19 January 2005

Abstract

We find that market efficiency increased and the arbitrage link between index futures and the stock market strengthened after June 24, 1997, when the New York Stock Exchange reduced the minimum change for stock prices and quotes from an eighth to a sixteenth of a dollar. There has been a substantial increase in the number of arbitrage trades reported to the Securities and Exchange Commission (SEC) since the reduction in the minimum price increment. The average number of stocks traded and the average dollar amount underlying each arbitrage trade increases and decreases, respectively. The average index futures mispricing error (MPE) that triggers arbitrage is lower and reverts to zero more quickly.

JEL classifications: G13; G14
Keywords: Index arbitrage; Equity index futures; S&P 500 futures; Minimum price increment

1. Introduction

On June 24, 1997, the New York Stock Exchange (NYSE) reduced the minimum change for stock prices and quotes from an eighth to a sixteenth of a dollar. The change

* Corresponding author. Tel.: +61 2 9385 5854; fax: +61 2 9385 6347.
E-mail address: t.henker@unsw.edu.au (T. Henker).

0927-5398/$ - see front matter
doi:10.1016/j.jempfin.2004.04.006

resulted in a decline in the quoted spread, e.g., see Bollen and Whaley (1998).[1] Our study investigates the impact of the decrease in spreads on S&P 500 index futures arbitrage. Lower transaction costs should result in a decrease in the index futures mispricing error (MPE) that triggers arbitrage. There are, however, a number of reasons why this expectation may be erroneous. First, Goldstein and Kavajecz (2000) and Jones and Lipson (2001) find that transaction costs decline only for small orders because cumulative market depth falls after the introduction of sixteenths. Second, Neal (1996) finds that arbitrageurs earn on average only around half the quoted spread for each round-trip arbitrage trade. Hence, for arbitrage to be profitable, arbitrageurs must be able to trade at prices inside the quoted spread. With these considerations in mind, we identify and investigate two important empirical questions. First, does the reduction of the minimum price increment affect the level of the mispricing error that triggers arbitrage, and second, has pricing efficiency improved under the new regime.

This study is different from existing studies in that it uses a unique combination of data sets. First, following Neal (1996), we use a data set of all actual S&P 500 index arbitrage trades in 1997, as reported to the Securities and Exchange Commission (SEC). Second, we obtained information from the NYSE stating when Rule 80A was triggered during 1997. In 1997, Rule 80A was triggered when the Dow Jones Industrial Average changed by 50 points from the previous day's close. Once activated on the sell (buy) side, it requires arbitrage orders to sell (buy) any component stock of the S&P 500 index to be entered with the instruction "sell plus" ("buy minus"). The rule specifies that a sell (buy) order can only be executed at a price above (below) the price of the preceding sale (buy). Overdahl and McMillan (1998) show that Rule 80A significantly curtails index arbitrage activity; hence, the MPE is expected to increase when the rule is in effect. Third, we compute a quote-based S&P 500 index using the midpoint of the last available bid-ask quote for each of the 500 constituent stocks. This quote-based index is less susceptible to the effects of stale transaction prices than the reported index and is free of the bid-ask bounce problem. Furthermore, the difference between the indices computed from the bid and from the ask quotes is a measure of time varying transaction costs.

We find that, after the introduction of sixteenths, the average dollar amount underlying each reported arbitrage trade dropped significantly from 16.5 million to 13.8 million, and the average number of stocks per arbitrage trade increased significantly from 355 to 379. Linking the exact times of the arbitrage trades reported to the NYSE to the spot and futures data, we find that, considering all arbitrage trades between 10:00 a.m. and 3:50 p.m. eastern standard time (EST), the average percentage MPE that triggers arbitrage is of similar size before and after sixteenths. Although this result is contrary to our expectations, a closer examination of the data reveals that the apparent lack of change may be due to increased stock market volatility in the second half of 1997. Higher volatility results in an increase in timing risk and in tracking error risk (i.e., the risk incurred from trading only a subset of the stocks underlying the index). When we condition all arbitrage trades on futures volatility in the 30 min prior to the arbitrage trade, we find a significant decrease in

[1] See also Harris (1997) for an overview of articles investigating reductions in the minimum price increment on the Toronto Stock Exchange, the AMEX, the Singapore Stock Exchange and the Australian Stock Exchange.

the average percentage MPE that triggers arbitrage. We also find that, after controlling for market risk, the mean reversion in the MPE is stronger after sixteenths, which may be explained by the significant increase in the average number of active arbitrageurs. Finally, irrespective of the change in the minimum price increment, when Rule 80A impedes the stock trades required for the arbitrage position, the MPE has to be significantly larger to trigger arbitrage.

The remainder of this paper is organized as follows. The next section describes the data, the S&P 500 ask and bid index construction, and the calculation of the index futures MPE. Section 3 reports on the identification of arbitrage opportunities and the sample characteristics of arbitrage opportunities before and after the introduction of sixteenths at the NYSE. Section 4 investigates the mean reversion in the MPE, and Section 5 concludes.

2. Data

2.1. Construction of the bid, ask, and trade-based S&P 500 index

The trades and quotes (TAQ) tapes from the NYSE include all trades and quotes for the 540 stocks that were included in the S&P 500 index for all or part of 1997. For these 540 stocks, we extract the last trade and bid and ask quotes from the primary exchange in 15-s intervals. For each day, we have 1561 observations, as the NYSE trades from 9:30 a.m. to 4:00 p.m. EST. We then filter the data for recording errors. The main filter eliminates large errors in trades and quotes that would seriously affect the index computation.[2] For stocks that do not have trades and/or quotes available immediately at the start of the trading day, we carry forward the prices and quotes of the previous trading day until the stock opens for trading. In the case of a stock split, the first available transaction price and quotes of the current trading day are used.

Standard & Poors provided the 500 index constituents for each trading day, as well as the number of shares used for each stock in the index calculation and the daily divisor for the index. The latter is adjusted daily so that the index returns are not affected by mergers or by removals or additions to the index. The S&P bid and ask indices are calculated every 15 s as

$$S_{t,i}^{\mathrm{BID}} = \sum_{n=1}^{500} s_{n,t} b_{n,t,i}/D_t, S_{t,i}^{\mathrm{ASK}} = \sum_{n=1}^{500} s_{n,t} a_{n,t,i}/D_t \tag{1}$$

where $s_{n,t}$ is the number of shares outstanding for stock n on day t, $a_{n,t,i}$ and $b_{n,t,i}$ are the ask and bid quotes for stock n on day t in 15-s interval i (i=1, …, 1561), and D_t is the

[2] For example, on April 17 at around 10:29 a.m., the trading prices for MSFT (Microsoft) are missing one digit, resulting in a price of \$9.95 instead of \$99.50. In addition, we exclude all prices or quotes that lead to immediate reversals (up–down or down–up) in excess of \$0.75, all cases where the bid exceeds the ask, and all observations for which the TAQ recording shows a trading halt, an (unrepaired) time stamp error, or another recording error. Potential smaller remaining errors will have little impact on the index calculation as the index is a weighted average of 500 prices or quotes.

divisor on day t. To monitor the accuracy of the index calculation procedure, we calculate a trade-based index using transaction prices. We compare this index to the intraday S&P index as reported to futures traders in the futures trading pit (and as provided to us by the Futures Industry Institute). The minimal deviations we find can be attributed to the fact that the S&P index is not displayed to futures traders in the trading pit on a precise 15-s grid. In addition, the S&P index lags our trade index slightly, probably due to the time it takes to process the last available transaction prices and disseminate the newly computed index to the market. The bid and ask indices are then used to compute a 'midpoint' index,

$$S_{t,i}^{\mathrm{MID}} = \left(S_{t,i}^{\mathrm{ASK}} + S_{t,i}^{\mathrm{BID}}\right)/2 = \sum_{n=1}^{500} s_{n,t}\left(a_{n,t,i} + b_{n,t,i}\right)/(2D_t) \tag{2}$$

Since there is a delay before each stock has traded for the first time on a new trading day[3] and since the bid-ask spread widens and quotes are older at the end of each trading day, the first 30 and the last 10 min of each day are excluded, leaving 1401 observations per day.

2.2. S&P 500 index futures

The Futures Industry Institute (FII) provided the transaction prices for the futures contracts on the S&P 500 index for 1997 and the March 1998 contract. At any given time, we consider the nearby contract until the Thursday one week prior to the maturity date of the nearby contract. From the Friday prior to the maturity date, we use the next maturing contract so that the maximum time to maturity of the contracts is 97 days. This schedule coincides with the day on which the next maturing contract surpasses the nearby contract in volume and the day on which the Chicago Mercantile Exchange (CME) redesignates the next maturing contract as the lead contract in the main trading pit (Kawaller et al., 2001). As with the stock prices and quotes, the last futures price for each 15-s interval is recorded from 8:30 a.m. to 3:00 p.m. CST. Excluding the first 30 and the last 10 min of trading leaves 1401 observations per day. For each 15-s interval, we determine the futures implied index, trade index, bid index, and ask index.

2.3. Construction of the S&P 500 index futures MPE

Futures and spot prices are linked by the cost-of-carry model,

$$F_{t,i} = \left(S_{t,i}^{\mathrm{MID}} - \mathrm{Div}_t\right)e^{-r_t(T-t)} \tag{3}$$

where $F_{t,i}$ is the futures price on day t in 15-s interval i, Div_t is the present value of the cash dividends that will be paid during the remaining life of the futures contract, and r_t is the risk-free rate of interest.

[3] See, for example, Aggarwal and Park (1994) for the effects of the staleness of the index at the start of the day. Using quotes does not alleviate this problem, as usually the first firm quote is posted after the first trade of the day.

Existing studies differ on the best way to utilize the cost-of-carry relationship to compute the mispricing error and corresponding arbitrage opportunities. We therefore estimate the MPE with two different methods, which we will call the market-implied MPE and the cost-of-carry MPE.

For the market-implied MPE, we refer to Dwyer et al. (1996), who infer the cost-of-carry term (dividends and interest rate) by imposing a zero mean on the mispricing error. The implicit assumption DLY make is that, on average, every trading day, the market is in equilibrium. We follow a similar approach with a slight variation since we express the MPE in index points. We define the futures implied index as

$$S_{t,i}^{\mathrm{FUT}} = F_{t,i} e^{\frac{1}{m}\sum \ln\left(S_{t,i}^{\mathrm{MID}}/F_{t,i}\right)} \tag{4}$$

where m is the number of observations per trading day, 1401 in our study. The market-implied MPE is then defined as

$$\mathrm{MPE}_{t,i} = S_{t,i}^{\mathrm{FUT}} - S_{t,i}^{\mathrm{MID}} \tag{5}$$

Most studies use actual dividends and actual interest rates to compute the mispricing error. Whereas Chung (1991) and Miller et al. (1994), for example, use the Treasury bill rate and MacKinlay and Ramaswamy (1988) use the higher Certificate of Deposit rate, we use the 3-month Eurodollar rate because it is the rate employed by most index arbitrageurs. Since the 1997 term structure for short-term rates is rather flat and arbitrageurs usually do not keep arbitrage positions until maturity, we did not try to find matching interest rates for each time to maturity. We use the actual cash dividends to compute the present value of the dividends. In addition, we consider the fact that stock prices usually do not drop by the full dividend. There is no consensus in the literature about the ratio of the ex-dividend day price drop to the amount of the dividend. For example, Koski (1996), Elton and Gruber (1970), and Kalay (1982) report ratios of price drop to dividend of 0.702, 0.778, and 0.881, respectively. To compute the ratio of the ex-dividend day price drop to the amount of the dividend for S&P stocks, we use all actual cash dividends for all of 1997 for all stocks included in the S&P 500 index. For each dividend, we determine the midpoint of the last quote for the stock (n) on the final day before the ex-dividend day, $P_{\mathrm{cum},n}$, the midpoint of the first firm quote for the stock on the ex-dividend day, $P_{\mathrm{ex},n}$, the closing midpoint index on the last day before the ex-dividend day, $\mathrm{S\&P}_{\mathrm{cum},n}$, and the midpoint index at 10:00 a.m. on the ex-dividend day, $\mathrm{S\&P}_{\mathrm{ex},n}$. Following Elton and Gruber (1970), the price drop dividend ratio (PDDR) is then computed as

$$\mathrm{PDDR} = \frac{1}{N}\sum_{n=1}^{N} \frac{P_{\mathrm{cum},n} - P_{\mathrm{ex},n} \times \dfrac{\mathrm{S\&P_{cum,n}}}{\mathrm{S\&P}_{\mathrm{ex},n}}}{\mathrm{Div_n}} \tag{6}$$

We calculate this ratio for 1997 to be 0.8313 with a standard error of 0.14. We then define the cost-of-carry mispricing error in index points,

$$\mathrm{MPE}_{t,i} = \left(F_{t,i} e^{-r(T-t)} + 0.8313\ \mathrm{Div}_t\right) - S_{t,i}^{\mathrm{MID}} \tag{7}$$

Interestingly, using this discount factor on the dividends has a similar effect to adding about 40 basis points to the Eurodollar interest rate, akin to Neal (1996) adding 88 basis points to the T-bill rate. Neal, using a data set of actual arbitrage trades, used Div_t and then inferred the interest rate such that the average mispricing error that triggered arbitrage would be the same for buy programs (buy index, sell futures) and sell programs (sell index, buy futures). This approach implicitly assumes that there are no short-sale constraints. We think our approach is more consistent with the literature on price drops on the ex-dividend day, and we think it is unlikely that the large investment banks that perform the arbitrage would pay such a high premium on the Treasury bill rate.

2.4. Sample statistics for the index and futures returns and the MPE

Index and futures 15-s returns are computed using log differences. Overnight returns are excluded. The data are divided into two subsamples. The first sample, before the introduction of sixteenths, from January 3rd through June 23rd, 1997, comprises 119 trading days with 1401 observations each. The second sample, from June 24th through December 23rd, 1997, but excluding October 27 and 28 due to extreme volatility and TAQ data recording problems, comprises 126 trading days. For more information on these 2 days, including arbitrage activity, see Ross and Sofianos (1998).

In Table 1, mean, standard deviation, and autocorrelation up to lag 4 are provided for index and futures returns and for the MPE.

As expected, the midpoint index volatility (0.00637 and 0.00763) is lower than the volatility of the trade index (0.00818 and 0.00843) because of the elimination of the bid-ask bounce. The smaller difference in panel (B) reflects the decrease in spreads and therefore in the bid and ask bounce. Furthermore, the autocorrelation in index returns is significantly larger for the midpoint index. As the fourth column of Table 1 shows, before the introduction of sixteenths, the trade price index has a first-order autocorrelation of 0.314 and the midpoint index a first-order autocorrelation of 0.678. The corresponding statistics after the introduction of sixteenths are 0.560 and 0.756, respectively. This difference is expected. The observed autocorrelation of the trade index comprises both a negative component caused by the bid-ask bounce and a positive component caused by the returns of the underlying index, whereas the midpoint index does not contain the negative autocorrelation component. This explanation suggests that existing studies may under-estimate the positive autocorrelation in index returns.

Futures volatility is considerably higher than the index volatility. Due to the bid-ask bounce, futures volatility will overestimate the volatility at the time of the arbitrage trade. Index volatility will underestimate this volatility due to the positive autocorrelation present in index returns. Miller et al. (1994) provide some theoretical results to support this assertion in a simple AR(1) framework. Miller, Muthuswamy and Whaley also report that the MPE is mean reverting regardless of the presence of an arbitrage opportunity. The statistics in Table 1 include all observations, the majority of which do not present arbitrage opportunities.

When comparing the cost-of-carry MPE with the market-implied MPE, there are some obvious differences. By construction, the market-implied MPE has a mean close to

Table 1
Properties of index and futures returns and the MPE

Series	Mean (%)	S.D. (%)	ρ_1	ρ_2	ρ_3	ρ_4
(A) Before the introduction of sixteenths at the NYSE (3 January–23 June, 1997)						
Trade index	0.0000385	0.00818	0.314	0.320	0.287	0.255
Midpoint index	0.0000376	0.00637	0.678	0.572	0.485	0.417
Futures	0.0000469	0.0243	−0.0972	0.0167	0.0134	0.0068
MPE (cost-of-carry)	0.00813	0.0782	0.950	0.910	0.873	0.841
MPE (market implied)	0.0000175	0.0591	0.912	0.841	0.777	0.719
(B) After the introduction of sixteenths at the NYSE (24 June–23 December, 1997)						
Trade index	−0.0000000345	0.00843	0.560	0.497	0.422	0.357
Midpoint index	−0.00000133	0.00763	0.756	0.633	0.528	0.443
Futures	−0.00000796	0.0286	−0.116	−0.00167	0.0110	0.0123
MPE (cost-of-carry)	0.0258	0.0722	0.919	0.857	0.804	0.760
MPE (market implied)	0.0000169	0.0582	0.874	0.779	0.697	0.628

Sample mean, standard deviation (S.D.), and autocorrelation (ρ) of trade index returns, midpoint index returns, futures returns, the mispricing error (MPE) according to the cost-of-carry model, and the market-implied MPE. The data frequency is 15-s intervals, with the first 30 and the last 10 min of each trading day excluded, leaving 1401 observations per day (except for July 3 and November 28, where the NYSE closed at 13:00 p.m.). Overnight price changes are excluded. The 'trade index' is the index value computed from the last transaction price for each stock prior to or on the 15-s mark. The 'midpoint index' is the average of the ask and bid indices, each of which is computed based on the last (ask and bid) quotes for each stock prior to or on the 15-s mark. The 'cost-of-carry' MPE is based on the cost-of-carry model using the 3-month Eurodollar interest rate and discounting the present value of actual dividends by a factor of 0.8313. The 'market-implied' MPE is constructed such that the average difference between the log futures price and log midpoint index for each trading day is equal to zero. Both MPEs are in percentage points, dividing the difference between the futures implied index and midpoint index by the midpoint index and multiplying by 100.

zero.[4] The cost-of-carry MPE, however, has a positive mean. The difference between the cost-of-carry MPE and the market-implied MPE translates into different profits for buy and sell programs. The gap between the two MPEs is especially large after the introduction of sixteenths. The mean cost-of-carry MPE could be reduced by using higher interest rates (a procedure followed by Neal, 1996) or by using a discount factor for the dividends that is lower than the 0.8313 we used. We leave this issue as an interesting area for future research.

3. Identifying arbitrage opportunities and SEC arbitrage trade reports

3.1. Identifying arbitrage opportunities and transaction costs

Arbitrage opportunities can be identified as follows.

Buy program: buy stocks, sell futures

$$\mathrm{MPE}_{t,i} > U_{t,i} \tag{8a}$$

[4] By construction, the market-implied MPE is $\ln(S_{t,i}^{\mathrm{FUT}}) - \ln(S_{t,i}^{\mathrm{MID}})$ which averages to precisely zero each day. However, we express the mispricing error in index points in Eq. (5), which has "a mean close to zero".

Sell program: sell stocks, buy futures

$$\mathrm{MPE}_{t,i} < -L_{t,i} \tag{8b}$$

An arbitrage buy program is initiated when the MPE exceeds the upper bound, $U_{t,i}$. An arbitrage sell program is initiated when MPE drops below the lower bound, $-L_{t,i}$. We believe that the complexity of index arbitrage makes it impossible to determine the upper and lower bounds using statistical models.[5] Numerous factors play a role in determining the arbitrage bounds, including Rule 80A, short-selling, tracking error, time-varying transaction costs, timing risk, dividend risk, interest rate risk, and the uncertain value of the early liquidation option (see Brennan and Schwartz, 1990). Miller et al. (1994) indicate that for constant U and L, many MPEs will be incorrectly identified as arbitrage opportunities. The identification of U and L is also made more difficult because the MPE is mean-reverting at any level and because, as shown in Table 1, U and L also depend on the method of calculating the MPE. For these reasons, we use the NYSE reports of the actual arbitrage trades.

Relieved of the need to estimate U and L, we will focus on the potential impact of sixteenths on transaction costs. We consider four different measures of the spread on the index. First, the quoted spread in index points is defined as

$$\mathrm{QSPREAD}_{t,i} = S_{t,i}^{\mathrm{ASK}} - S_{t,i}^{\mathrm{BID}} = \sum_{n=1}^{500} s_{n,t}\ \left(a_{n,t,i} - b_{n,t,i}\right)/D_t \tag{9}$$

Second, we define the relative quoted spread,

$$\mathrm{QSPREAD\_REL}_{t,i} = 100\ \left(S_{t,i}^{\mathrm{ASK}} - S_{t,i}^{\mathrm{BID}}\right)/S_{t,i}^{\mathrm{MID}}. \tag{10}$$

As one would expect in an efficient market, the S&P index arbitrage market is very competitive, and arbitrage opportunities are short lived. Most index arbitrage groups are proprietary trading desks of investment banks and brokerage firms who have access to in-house order flow. Frequently, arbitrage opportunities are solitary events in that only a single arbitrage trader faces order flow that permits a profitable trade. Neal (1996) reports that arbitrageurs earn on average less than half the quoted spread per trade. To be profitable, arbitrageurs must therefore be able to trade inside the quoted spread, and indeed, most arbitrage transactions in our sample are initiated when transaction prices are still within the bid and ask bounds of the index. For these reasons, the effective spread is of interest. The effective spread for each stock is calculated as twice the deviation of the transaction price from the quote midpoint. The effective spreads are then weighted according to each stock's weight in the index, and the spread is again computed in both index points and percentage points:

$$\mathrm{ESPREAD}_{t,i} = \sum_{n=1}^{500} s_{nt}\ \left|2\ \left[\left(a_{n,t,i} + b_{n,t,i}\right)/2 - p_{n,t,i}\right]\right|/D_t \tag{11}$$

[5] Threshold autoregressive models can determine a constant threshold. This tool is used, for example, by Dwyer et al. (1996) and Martens et al. (1998).

and

$$\text{ESPREAD\_REL}_{t,i} = 100\left(\sum_{n=1}^{500} s_{nt}\left|2\left[\left(a_{n,t,i}+b_{n,t,i}\right)/2 - p_{n,t,i}\right]\right|\right)/D_t/S_{t,i}^{\text{MID}} \tag{12}$$

where $p_{n,t,i}$ is transaction price for stock n on day t in 15-s interval i. The characteristics of these spread measures for the S&P 500 are provided in panel (A) of Table 2.

As previously documented in Bollen and Whaley (1998) and Goldstein and Kavajecz (2000), the introduction of sixteenths on the NYSE reduced bid and ask spreads and therefore trading costs. The results in panel (A) of Table 2 show a reduction in relative quoted spreads from 0.300% to 0.213%. In index points, the quoted spread decreased from 2.40 to 2.00. Interestingly, the volatility of the spread increased from 10.3% to 19.4% for the quoted spread. Akin to the quoted spreads, after the introduction of sixteenths, the effective spread decreased from 1.59 index points to 1.15 index points. Comparing the quoted and effective spreads shows how much can be saved if a substantial number of the stocks underlying the index are traded without specialist participation. For example, the ‘after sixteenths’ quoted spread is 2.00 index points compared to an effective spread of 1.15 index points. This is a large difference, especially considering that the gross return on an ‘after sixteenths’ round-trip arbitrage[6] trade is only about 1.84 index points for the cost-of-carry MPE and 1.53 index points for the market-implied MPE.

The potential cost reduction is further investigated by considering the case in which an arbitrageur buys a subsample of the stocks underlying the S&P 500 index. Arbitrageurs accept the resulting tracking error in return for a cost reduction and the ability to buy only the most liquid stocks, guaranteeing the speed necessary to acquire the arbitrage position. In addition, Rule 80A at times allows arbitrageurs to buy or sell only a limited number of stocks within a reasonable amount of time. Overdahl and McMillan (1998) find that Rule 80A has little impact on trading costs and intermarket arbitrage but appears to significantly curtail index arbitrage volume. Table 2 also shows the spread related transaction costs of buying the N cheapest (panel [B]) or the N largest stocks (panel [C]) from the S&P index universe.

Panels (B and C) of Table 2 show that substantial cost savings are possible by trading a subsample of the 500 stocks underlying the S&P 500 index. For example, for arbitrageurs buying only the cheapest 150 stocks, the average quoted spread in index points reduces from 2.40 to 1.41 prior to sixteenths and from 2.00 to 1.07 after sixteenths. These 150 stocks have a combined weight of over 50% in the index, and this portfolio could well be sufficient to obtain an acceptable level of tracking error. The decrease in the effective spread with the introduction of sixteenths is of similar relative magnitude. In panel (C), the stock portfolios are formed by market capitalization rather than by the spread. The results are qualitatively similar to those in panel (B), but smaller gains are obtained for the effective spread.

[6] A round-trip arbitrage would involve setting up, for example, a buy program (buy stocks, sell futures) when the MPE is positive and liquidating this position prior to maturity when the MPE is negative (liquidating the position is equivalent to setting up a new position that involves selling stocks and buying futures).

Table 2
The S&P 500 index bid-ask spread and the cost of tracking the index using fewer than 500 stocks

	January 3–June 23, 1997 (before introduction of sixteenths)				June 24–December 23, 1997 (after introduction of sixteenths)			
(A) Descriptive S&P 500 index spread statistics								
	Quoted spread	Effective spread	Quoted spread	Effective spread	Quoted spread	Effective spread	Quoted spread	Effective spread
	(index points)		(percentage)		(index points)		(percentage)	
Mean	2.40	1.59	0.300	0.198	2.00	1.15	0.213	0.122
S.D.	0.103	0.0919	0.0179	0.0122	0.194	0.179	0.0208	0.0192
Max.	3.63	2.85	0.435	0.345	4.06	5.13	0.440	0.550
Min.	2.06	1.19	0.240	0.142	1.43	0.802	0.156	0.0860
Number of stocks	Quoted spread		Effective spread		Quoted spread		Effective spread	
	Spread in index points	Proportion of index	Spread in index points	Proportion of index	Spread in index points	Proportion of index	Spread in index points	Proportion of index
(B) Stocks sorted on percentage spread, include cheapest								
50	1.01	0.273	0.00	0.100	0.77	0.247	0.00	0.10
100	1.27	0.464	0.02	0.190	0.92	0.394	0.01	0.20
150	1.41	0.571	0.37	0.400	1.07	0.517	0.21	0.37
200	1.55	0.670	0.68	0.570	1.20	0.628	0.44	0.56
250	1.68	0.750	0.90	0.710	1.33	0.721	0.57	0.68
300	1.81	0.823	1.05	0.790	1.44	0.798	0.68	0.77
350	1.94	0.881	1.19	0.870	1.57	0.866	0.78	0.85
400	2.07	0.929	1.32	0.930	1.69	0.922	0.89	0.92
450	2.22	0.970	1.44	0.970	1.82	0.966	1.00	0.97
500	2.40	1.000	1.59	1.000	2.00	1.000	1.16	1.00
(C) Stocks sorted on market capitalization, include largest								
50	1.76	0.487	1.21	0.490	1.55	0.491	0.91	0.49
100	1.91	0.656	1.30	0.660	1.66	0.660	0.98	0.67
150	2.02	0.754	1.36	0.750	1.72	0.759	1.01	0.77
200	2.10	0.826	1.41	0.830	1.78	0.830	1.04	0.84
250	2.18	0.878	1.45	0.880	1.83	0.881	1.06	0.89
300	2.23	0.920	1.48	0.920	1.87	0.921	1.09	0.93
350	2.28	0.952	1.51	0.950	1.91	0.952	1.11	0.96
400	2.32	0.976	1.54	0.980	1.94	0.976	1.12	0.98
450	2.36	0.992	1.56	0.990	1.97	0.991	1.14	1.00
500	2.40	1.000	1.59	1.000	2.00	1.000	1.16	1.00

Sample mean, standard deviation, maximum, and minimum of the S&P 500 index bid-ask spread. The quoted spread is the difference between the ask index and the bid index (in index points) or the difference between the ask index and bid index divided by the midpoint index (relative spread). The effective spread is the market capitalization weighted effective spread of the 500 stocks comprising the index, where the effective spread for each stock is computed as the absolute difference between the midpoint of the stock's bid and ask quotes and the stock's trading price (in index points). The relative effective spread is the effective spread in index points divided by the midpoint index. Proportion of the index covered is the market capitalization of the sample divided by total market capitalization. The included stocks are either selected based on the cheapest relative spreads (B) or based on the largest market capitalization stocks (C). The data frequency is 15-s intervals, with the first 30 and the last 10 min of each trading day excluded, leaving 1401 observations per day (except for July 3 and November 28, where the NYSE closed at 13:00 p.m.).

3.2. Sample characteristics of arbitrage trades

The SEC requires the reporting of all program trades (a trade in which 15 stocks or more are traded at the same time) by member firms of the exchange. We obtained these daily program trading records from the NYSE for 1997. For each index arbitrage trade, the data contain the submission time (to the nearest minute or to the nearest second[7]) for both the stock and corresponding futures trade and whether the trade is a buy (buy stocks, sell futures) or a sell (sell stocks, buy futures) or short sell (short sell stocks, buy futures). In addition, the data show the number of stocks involved in the trade,[8] the dollar volume of the stock position, the number of futures contracts, and the maturity of the futures contracts.[9]

The sample characteristics of arbitrage trades between 10:00 a.m. and 3:50 p.m. before and after the introduction of sixteenths are presented in Table 3.[10]

The daily program trading reports show that the average dollar amount underlying each trade drops significantly from 16.5 to 13.8 million dollars, with a z-statistic of 15.2.[11] The average number of stocks underlying each arbitrage trade increased significantly from 355 to 379, with a z-statistic of 8.1. With the reduced spreads, it is possible to buy more stocks at lower costs, thereby reducing tracking error. The average number of shares traded per stock decreased from 898 to 723 after the introduction of sixteenths. Therefore, the reduced average size of arbitrage trades is probably a reflection of the reduced depth of the best quotes. Similar conclusions apply to the various categories of arbitrage trades, i.e., buy programs, sell programs, and in periods when rule 80A is inactive and active. The only exception is for short-sell programs where there is little difference in the average dollar value and number of stocks underlying the 176 arbitrage trades before sixteenths and the 172 trades after sixteenths.

---

[7] 43% to 50% of the time stamps are rounded to the nearest minute. For this reason the time-series analysis in Section 4 is at the 1- and 2-min frequency. The MPE statistics below are based on the original SEC time stamps matched with futures and stock trades that are time stamped to the second. The actual arbitrage trade may have taken place before or after the minute mark for observations with rounded time stamps. However, Fig. 1 in Section 4 supports our approximation, as the MPE peaks at the time stamps provided in the SEC files.

[8] Often, an arbitrage trade has two separate entries in our data set that directly follow each other. Generally, the first entry specifies the trade for the stocks on the NYSE, whereas the second (smaller) trade specifies the trade of the NASDAQ stocks that are part of the S&P 500 index. These related entries are aggregated for the analysis.

[9] Like Neal (1996), we filtered the data for errors. Obvious typing errors have been corrected. Entries for which the futures and equity time stamps are more than 15 min apart are eliminated. Trades that include 40 or fewer stocks (after NASDAQ trades are combined with NYSE trades) are eliminated. The time stamp used for computing all arbitrage related statistics is determined by the earliest time, either the time for the stock or for the futures trade. Trades where the absolute difference between the dollar value underlying the stock and futures trades is more than 40% of the dollar value underlying the stock trade are eliminated. Lastly, trades for which the average price per share is lower than \$10 or higher than \$100 are eliminated.

[10] Tables 3 and 4 for the time period 9:30–16:00 are available from the authors upon request. The results are robust towards the choice of sample period, but the standard deviations of point estimates are generally higher due to the larger volatility immediately after the market opening and before market closing.

[11] If X_m is the mean trade value in panel (B), Y_n is the mean trade value in Panel (A), σ_m and σ_n are their respective standard deviations, and m and n their respective number of observations the $N(0,1)$ distributed test statistic is $Z = \frac{(\bar{X}_m - \bar{Y}_n)}{\left(\frac{\hat{\sigma}_m^2}{m} + \frac{\hat{\sigma}_n^2}{n}\right)^{1/2}}$.

Table 3
Sample characteristics of S&P 500 index arbitrage trades

Variable	Buy programs (buy stock, sell futures)			Direct sell programs (sell stock, buy futures)			Short-sell programs (short-sell stock, buy futures)			All
	All	80A	No 80A	All	80A	No 80A	All	80A	No 80A	
(A) Before introduction of sixteenths at the NYSE (3 January–23 June, 1997)										
Cost-of-carry MPE (%)	0.102 (0.0674)	0.132 (0.0822)	0.0946 (0.0608)	−0.101 (0.0827)	−0.181 (0.134)	−0.0914 (0.0688)	−0.129 (0.105)	−0.156 (0.118)	−0.0893 (0.0658)	0.103 (0.0772)
Market-implied MPE (%)	0.0721 (0.0592)	0.0817 (0.0742)	0.0696 (0.0544)	−0.0862 (0.0681)	−0.127 (0.127)	−0.0815 (0.0555)	−0.0907 (0.0919)	−0.100 (0.106)	−0.0771 (0.0633)	0.0793 (0.0658)
Cost-of-carry MPE (index points)	0.830 (0.551)	1.08 (0.682)	0.765 (0.492)	−0.787 (0.640)	−1.41 (1.04)	−0.715 (0.532)	−0.998 (0.808)	−1.21 (0.901)	−0.685 (0.508)	0.821 (0.610)
Market-implied MPE (index points)	0.578 (0.474)	0.666 (0.607)	0.555 (0.430)	−0.681 (0.535)	−1.00 (1.00)	−0.644 (0.437)	−0.709 (0.719)	−0.788 (0.833)	−0.593 (0.489)	0.631 (0.520)
Dollar value stocks (millions)	16.9 (8.37)	17.7 (8.58)	16.6 (8.30)	16.3 (7.77)	16.6 (8.04)	16.3 (7.74)	15.3 (7.76)	17.2 (8.10)	12.6 (6.33)	16.5 (8.09)
Number of stocks	357 (128)	313 (126)	369 (126)	361 (124)	290 (134)	369 (120)	289 (131)	314 (120)	253 (140)	355 (127)
Number of shares per stock	898 (391)	1032 (385)	864 (385)	879 (378)	1075 (384)	857 (371)	1036 (407)	1032 (363)	1042 (467)	898 (387)
Sample size	1587	326	1261	1391	145	1246	176	105	71	3154
(B) After introduction of sixteenths at the NYSE (24 June–23 December, 1997)										
Cost-of-carry MPE (%)	0.114[a] (0.0578)	0.136 (0.0611)	0.109[a] (0.0557)	−0.0835[a] (0.0787)	−0.135[a] (0.103)	−0.0726[a] (0.0679)	−0.114 (0.100)	−0.122[a] (0.0963)	−0.0520 (0.113)	0.102 (0.0708)
Market-implied MPE (%)	0.0770[a] (0.0610)	0.0741 (0.0627)	0.0777[a] (0.0606)	−0.0872 (0.0718)	−0.108 (0.105)	−0.0828 (0.0620)	−0.0905 (0.0949)	−0.0946 (0.0944)	−0.0555 (0.0937)	0.0817 (0.0674)
Cost-of-carry MPE (index points)	1.07[a] (0.536)	1.27[a] (0.563)	1.02[a] (0.517)	−0.773 (0.727)	−1.25 (0.953)	−0.672[b] (0.626)	−1.06 (0.920)	−1.12 (0.882)	−0.474 (1.05)	0.947[a] (0.656)
Market-implied MPE (index points)	0.718[a] (0.562)	0.693 (0.578)	0.724[a] (0.558)	−0.809[c] (0.664)	−1.00 (0.968)	−0.768[c] (0.573)	−0.835 (0.871)	−0.873 (0.866)	−0.509 (0.869)	0.760[a] (0.622)
Dollar value stocks (millions)	13.4[c] (6.53)	15.9[c] (8.01)	12.7[c] (5.94)	14.2[c] (7.54)	16.1 (9.56)	13.8[c] (6.98)	15.2 (9.05)	15.9 (9.02)	8.71[d] (6.42)	13.8[c] (7.09)
Number of stocks	388[a] (124)	344[a] (133)	398[a] (119)	377[a] (128)	303 (149)	392[a] (117)	288 (140)	300 (134)	188 (153)	379[a] (128)
Number of shares per stock	674[c] (356)	840[c] (341)	633[c] (347)	761[c] (441)	1003 (454)	711[c] (422)	1012 (611)	1022 (634)	927[c] (360)	723[c] (412)
Sample size	2360	466	1894	1779	307	1472	172	154	18	4311

Sample means for the cost-of-carry MPE (percentage or index points), the market-implied MPE (percentage or index points), the dollar value per arbitrage trade in millions, the number of stocks, and the number of shares per arbitrage trade. The sample covers all index arbitrage trades reported to the NYSE from January 3 to June 23, 1997 (A), and June 24 to December 23, 1997 (B), between 10:00 a.m. and 3:50 p.m. EST. '80A' ('No 80A') indicates Rule 80A is (not) active and relevant for the buy or sell program at the time of the arbitrage trade. The 'cost-of-carry' MPE is based on the cost-of-carry model using the 3-month Eurodollar interest rate and discounting the present value of actual dividends by a factor 0.8313. The 'market-implied' MPE is constructed such that the average difference between the log futures price and log midpoint index for each trading day is equal to zero. MPEs in percentage points are computed by dividing the difference between the futures implied index and midpoint index by the midpoint index and multiplying by 100. The MPE in index points is the difference between the futures implied index and midpoint index. Standard deviations are in parentheses.

[a] Indicates that the mean in panel (B) is significantly larger than the corresponding mean in panel (A) at the 1% significance level, respectively.

[b] Indicate that the mean in panel (B) is significantly larger than the corresponding mean in panel (A) at the 5% significance level, respectively.

[c] Indicate that the mean in Panel (B) is significantly smaller than the corresponding mean in Panel (A) at the 1% significance level, respectively.

[d] Indicate that the mean in Panel (B) is significantly smaller than the corresponding mean in Panel (A) at the 5% significance level, respectively.

It is also interesting to consider total arbitrage activity before and after sixteenths, measuring the net effect of more frequent arbitrage trades and a lower dollar volume. In the 119 days prior to sixteenths, the average daily dollar volume of index arbitrage trading is \$438.6 million. In the 126 days after sixteenths, the average daily dollar volume is \$471.5 million. This is a statistically insignificant increase of 7.5%. For the full trading day from 9:30 to 16:00, the (statistically insignificant) increase in average daily dollar volume is 6.8%. For the same two time periods, the dollar trading volume for all S&P stocks increased statistically significantly by 13.8%. Apparently, the dollar value of index arbitrage activity decreased relative to other types of trading motives.

Table 3 also reports the results for the mispricing errors defined in Eqs. (5) and (7). Given the substantial reduction in transaction costs after the introduction of sixteenths, it is surprising to note that the average MPE that prevails when arbitrage trades are initiated is little changed regardless of how the mispricing error is constructed. For example, the average cost-of-carry MPE (market-implied MPE) that triggers arbitrage is 0.103% (0.0793%) before sixteenths and 0.102% (0.0817%) after sixteenths.[12] The MPEs in index points increase after sixteenths, but this is due to the increased level of the index (the average index level is 938.77 after sixteenths, as opposed to 801.23 before sixteenths).

With the results presented in the first nine columns of Table 3, we investigate in greater detail the differences between buy and sell programs and the impact of Rule 80A. First, we consider the difference between buy and sell programs. The assumptions underlying the market-implied MPE suggest that the MPEs should be symmetric, but the table shows that sell programs are executed at a significantly higher MPE than are buy programs. This result differs from the findings of DLY who observe no asymmetry. For the cost-of-carry MPE, no difference is found in panel (A), but in panel (B), buy programs require a significantly higher MPE than do sell programs. As discussed in Section 2.4, using too high a price drop to dividend ratio after sixteenths may cause this imbalance. Hence, it is difficult to reach any conclusion regarding asymmetry between buy and sell programs.

For both MPE measures, Rule 80A has a significant impact on arbitrageurs' decisions of when and how to initiate trades. Significantly fewer stocks are used for arbitrage trades when Rule 80A is in effect. This suggests that Rule 80A forces arbitrageurs to execute arbitrage trades with smaller portfolios of stocks, which in turn presumably results in higher tracking error and therefore increased risk for the arbitrageur. Accordingly, for all MPE measures, the average MPE that triggers arbitrage is significantly higher when Rule 80A is in effect. For example, the average cost-of-carry MPE for buy programs prior to sixteenths is 1.08 index points when Rule 80A is in effect and 0.765 index points when Rule 80A is not applicable. These results provide additional insights into the effects of Rule 80A on arbitrage.

That the introduction of sixteenths does not apparently affect MPEs merits further investigation to identify other characteristics of the two periods that may affect arbitrageurs' decisions of when to initiate arbitrage trades. An obvious candidate is the

[12] The conclusions here and below are not affected by using the median instead of the mean MPE.

risk of initiating the position. Table 1 shows that the volatility in the second half of the year was much higher than in the first half. Increased volatility of the futures and the underlying market will increase the execution risk for the position. In periods of high volatility, one would expect arbitrageurs to initiate trades only at relatively higher MPEs to compensate for the increased price risk of nonsimultaneous order execution.

3.3. Conditioning mispricing errors on volatility

We hypothesize that the MPE is reduced by the introduction of sixteenths, but that any reduction is offset by the higher market volatility in the second half of 1997. Table 4 conditions the data in the two panels on the 30-min volatility of the futures returns immediately preceding the arbitrage event. We choose the futures volatility over the volatility of the underlying stocks because the bid-ask bounce in futures prices is regarded

Table 4
Mean mispricing errors conditional upon futures volatility

Futures volatility range in percent	All buy and sell programs, no Rule 80A			
	MPE (%) cost-of-carry	MPE (%) market implied	Bid-ask spread	Sample size
(A) Before introduction of sixteenths at the NYSE (3 January–23 June, 1997)				
<0.015 (<9.4% p.a.)	0.0766 (0.0481)	0.0528 (0.0360)	0.290 (0.0149)	187
0.015–0.020 (9.4–12.5% p.a.)	0.0811 (0.0537)	0.0619 (0.0447)	0.297 (0.0170)	703
0.020–0.025 (12.5–15.6% p.a.)	0.0892 (0.0632)	0.0704 (0.0508)	0.302 (0.0158)	701
0.025–0.030 (15.6–18.7% p.a.)	0.103 (0.0697)	0.0907 (0.0574)	0.308 (0.0163)	409
0.030–0.035 (18.7–21.9% p.a.)	0.108 (0.0603)	0.0941 (0.0585)	0.312 (0.0128)	147
0.035–0.040 (21.9–25.0% p.a.)	0.115 (0.0869)	0.104 (0.0884)	0.310 (0.0146)	77
>0.040 (>25.0% p.a.)	0.0960 (0.0925)	0.0927 (0.0805)	0.323 (0.0191)	147
Average of five middle ranges	0.0992	0.0843		
(B) After introduction of sixteenths at the NYSE (24 June–23 December, 1997)				
<0.015 (<9.4% p.a.)	0.0793 (0.0583)	0.0646 (0.0459)	0.199 (0.0141)	106
0.015–0.020 (9.4–12.5% p.a.)	0.0840 (0.0509)	0.0591 (0.0380)	0.204 (0.0152)	625
0.020–0.025 (12.5–15.6% p.a.)	0.0831** (0.0510)	0.0681 (0.0415)	0.214 (0.0173)	670
0.025–0.030 (15.6–18.7% p.a.)	0.0804** (0.0604)	0.0758** (0.0615)	0.218 (0.0179)	501
0.030–0.035 (18.7–21.9% p.a.)	0.0869** (0.0686)	0.0810** (0.0599)	0.220 (0.0200)	333
0.035–0.040 (21.9–25.0% p.a.)	0.100 (0.0670)	0.0900 (0.0634)	0.226 (0.0186)	270
>0.040 (>25.0% p.a.)	0.114 (0.0871)	0.116 (0.095)	0.249 (0.0316)	453
Average of five middle ranges	0.0869**	0.0748**		

Mean percentage mispricing errors (MPEs) and mean bid-ask spreads for all buy and sell programs, excluding cases where Rule 80A was effective, are reported conditioned on the standard deviation of 15-s futures returns in the 30 min prior to the arbitrage trade. The 'cost-of-carry' MPE is based on the cost-of-carry model using the 3-month Eurodollar interest rate and discounting the present value of actual dividends by a factor 0.8313. The 'market-implied' MPE is constructed such that the average difference between the log futures price and log midpoint index for each trading day is equal to zero. MPEs in percentage points are computed by dividing the difference between the futures implied index and midpoint index by the midpoint index and multiplying by 100. Standard deviations are provided in parentheses. ** and * indicate that the mean MPE after sixteenths is significantly (at the 1% and 5% level, respectively) smaller than the mean MPE before sixteenths in the corresponding volatility range (and corresponding MPE measure).

to be a less serious problem than the serial correlation in index returns.[13] The bid-ask bounce is present in all volatility categories and therefore should not affect the categorization of the data. Table 4 presents the results for all arbitrage trades that were not impeded by Rule 80A.

Volatility increased substantially in the second part of 1997, as is evidenced by the much larger number of observations in the three highest volatility brackets in panel (B) than in panel (A). Table 4 also shows that the higher the (index futures) volatility, the higher the average MPE that triggers arbitrage. For example, the cost-of-carry MPE in panel (B) averages 0.0793% for the lowest volatility range and increases to 0.114% for the highest volatility range. The higher volatility after the introduction of sixteenths creates the impression in Table 3 that the reduction of transaction costs had little impact on the average MPE that triggers arbitrage.

After we control for the increased volatility, we find a significant reduction in the average MPE that triggers arbitrage after the introduction of sixteenths. The mean of the average market-implied MPE for the five middle volatility ranges (0.015–0.020, ..., 0.035–0.040) is 0.0843% before and 0.0748% after sixteenths. For the cost-of-carry MPE, the mean is 0.0992% before and 0.0869% after sixteenths.[14] If we construct a new series by computing the difference in average MPE for each volatility category before and after sixteenths, we find that for both the cost-of-carry MPE and the market-implied MPE, there is a significant drop in the average MPE that triggers arbitrage. Panel (B) of Table 4 indicates the significance level of the differences in the conditional MPEs between panels (A and B). For the MPEs of individual volatility categories, a differences in means test[15] is reported. To test for the significance in the aggregated difference in the MPE for the five middle volatility categories, a joint test for differences in averages[16] is applied that follows an asymptotically normal distribution. The differences in averages before and after the introduction of sixteenths are significant with z-statistics of 2.6 and 3.3 for the cost-of-carry and market-implied MPE, respectively. For the market-implied MPE, we find even larger differences before and after sixteenths for sell programs (results not reported in Table 4). The mean of the average MPE for the five middle volatility ranges is −0.0939% before sixteenths and −0.0777% after sixteenths. This change translates into a reduction of 0.0162% or 0.1458 index points for an S&P index level of 900.

[13] In aggregate, the results of Table 4 are similar if arbitrage trades are conditioned on spot price and futures volatility as opposed to futures price volatility alone. Results are also robust if a 15-min window is used to estimate volatility. As expected, the significance of the results deteriorates if the time period for the volatility estimation is lengthened because the volatility perceived by traders at the time of the arbitrage trade cannot be accurately estimated with a sample that includes observations that are too far removed in time.

[14] To get a feeling for these differences in economic terms, consider the situation where the S&P index is at 900. A difference of 0.0922%−0.0869%=0.0053% translates into 0.0477 index points. Compare this to a 0.40 index points reduction in the average quoted spread or 0.20 index points for a one-way trip. For the market-implied MPE, the difference of 0.0843%−0.0748%=0.0095% translates into 0.0855 index points.

[15] The test statistic is the same as in Footnote 10. Here, X_m is the mean MPE in panel (B), Y_n is the mean MPE in panel (A), σ_m and σ_n are their respective standard deviations, and m and n their respective number of observations.

[16] $Z = \frac{m^{1/2}(\bar{X}_m - 0)}{\hat{\sigma}_m}$, where m is number of observations (5 in this case), X_m is the mean difference, and $\hat{\sigma}_m$ is the standard deviation of the five differences.

To test the robustness of these important results, we implement the methodology of Jones and Lipson (2001). The goal is to test whether the introduction of sixteenths reduced the average mispricing error that triggers arbitrage while controlling for changes in the volatility and other control variables. We estimate the regression in Eq. (13) for all arbitrage trades prior to sixteenths and use the estimated coefficients to calculate MPE prediction errors under 16th in Eq. (14).

$$\mathrm{MPE}^{8}_{i,t} = \alpha + \beta_1 \mathrm{VOLA}_{i,t} + \beta_2 \mathrm{RULE80A}_{i,t} + \beta_3 \mathrm{BUY}_{i,t} + \beta_4 \mathrm{SHORT}_{i,t} + e^{8}_{i,t} \quad (13)$$

where $\mathrm{MPE}_{i,t}$ is the percentage mispricing error on day t and intraday period i, while the superscript indicates the minimum price increment at the period, $\mathrm{VOLA}_{i,t}$ is the futures volatility in the 30 min prior to the arbitrage trade at time i, $\mathrm{RULE80A}_{i,t}$ is an indicator variable that assumes the value one if Rule 80A inhibited the arbitrage trade and zero otherwise, $\mathrm{BUY}_{i,t}$ is an indicator variable with value one if the arbitrage trade is a buy program and zero otherwise, and $\mathrm{SHORT}_{i,t}$ is an indicator variable with value one if the arbitrage trade involved short selling and zero otherwise. We do not control for the prevailing spread since the reduced spreads are the reasons why we expect the mispricing error to be smaller when arbitrage programs are initiated.

The coefficient estimates[17] from Eq. (13) are then used to predict the MPEs after the introduction of sixteenths and, to compute the prediction errors,

$$\hat{e}^{16}_{i,t} = \mathrm{MPE}^{16}_{i,t} - \hat{\alpha} - \hat{\beta}_1 \mathrm{VOLA}_{i,t} - \hat{\beta}_2 \mathrm{RULE80A}_{i,t} - \hat{\beta}_3 \mathrm{BUY}_{i,t} - \hat{\beta}_4 \mathrm{SHORT}_{i,t} \quad (14)$$

where the hats for the coefficient estimates indicate the previously estimated coefficients are used. We can now, while controlling for volatility and Rule 80A, test whether arbitrage trades are triggered at a lower mispricing error after the introduction of sixteenths. The null hypothesis of the test is H_0: $\bar{\hat{e}}^{8}_{i,t} = \bar{\hat{e}}^{16}_{i,t}$, while the alternative hypothesis is H_A: $\bar{\hat{e}}^{8}_{i,t} > \bar{\hat{e}}^{16}_{i,t}$. The bars indicate that we compute the average over all residuals. Obviously, the average residual before sixteenths equals zero by construction. To test the hypothesis, the same test statistic is used as in Footnote 11. For the cost-of-carry MPE, the test statistic equals 4.35, whereas for the market-implied MPE, the test statistic is equal to 6.54. In both cases, the null hypothesis is rejected in favor of the alternative hypothesis at any conventional significance level.

This test supports the conclusion from Table 4 that the average mispricing error when index futures arbitrage trades take place is significantly lower after the introduction of sixteenths, when controlling for volatility and Rule 80A. The magnitude of the difference is less than half the reduction in transaction costs as measured by the quoted and effective spreads. The result from Table 4 further illustrates the ability of arbitrageurs to trade inside the quoted spread and to avoid trading with the market makers for at least some of the stocks, thus reducing the benefit of the decreased spreads. The cost benefits from the reduction in the minimum price increment are potentially larger for institutional arbitrageurs. However, they face higher commission costs. They also have a lesser ability to internally match client orders and trade with other member firms and thereby reduce

[17] A table with the regression results is available upon request.

transaction costs incurred by trading through the market makers. In spite of these qualifications, the reduction in the minimum price increment does have the effect of reducing the magnitude of mispricing errors that trigger arbitrage.

4. Mean reversion of the MPE

A consequence of index arbitrage is that any mispricing between the futures price and the index value dissipates quickly. To evaluate the validity of this statement and to gain additional insight into the process of mean reversion of the market-implied MPE, Fig. 1 presents an event study type plot of mispricing.[18] The graph centers on the event of index arbitrage trades. The deviation from fair value is examined for the interval from 10 min prior to the arbitrage trade to 10 min after the arbitrage trade.

Fig. 1 is similar in format to Fig. 2 in Neal (1996), except that we represent the MPE before and after sixteenths separately and in percentage points rather than index points. Consistent with our expectations, we find clear evidence of mean reversion. Within 5 min after the arbitrage trade event, the mean mispricing decays more than 75%. The speed of decay accelerates for the period after the introduction of sixteenths, particularly for the sell programs. An indication for increasing competition among arbitrageurs in 1997 is that, after sixteenths were introduced, it took an average of 2.25 (4) min, for market-implied (cost-of-carry) MPEs to halve after arbitrage transactions were initiated. This is 45 s (1 min) less than in the first part of the year. Regardless of the method of MPE calculation, the acceleration in mean reversion is pervasive. It is interesting to note that, in his sample from early 1989, Neal finds MPEs declining by only about 50% even after 10 min.

To quantify the mean reversion of the MPE more accurately, we use the following model adapted from Balke and Fomby (1997),

$$\mathrm{MPE}_t = a_0 + \sum_{k=1}^{5} a_k\ \mathrm{MPE}_{t-k} + \sum_{k=1}^{5} b_k\ \ln\left(S_{t-k}^{\mathrm{MID}}/S_{t-1-k}^{\mathrm{MID}}\right) + \varepsilon_t \tag{15}$$

where $t-1$ is the time stamp of the arbitrage trade in the SEC files.[19] Coefficient estimates for a_1 are reported in Table 5. Existing studies rely on an estimated constant threshold variable to divide the data into three regimes ('buy programs,' 'no arbitrage,' and 'sell programs'). This assumption leads to many observations being incorrectly identified as arbitrage opportunities (Miller et al., 1994). Rather than following this static approach, we categorize the data using the actual arbitrage transactions as reported to the SEC.

Based on the evidence in Fig. 1 of the duration of arbitrage opportunities, we calculate the mean reversion coefficient 1 and 2 min before and after arbitrage trades. The time series in the no-arbitrage regime displays mean reversion in the MPE for reasons discussed

[18] Using the cost-of-carry MPE instead of the market-implied MPE does not materially change Fig. 1.

[19] We would like to thank an anonymous referee for pointing out that by including the lagged index returns in Eq. (15), the model is consistent with Engle and Granger's (1987) vector error correction model (VECM) for futures and index returns.

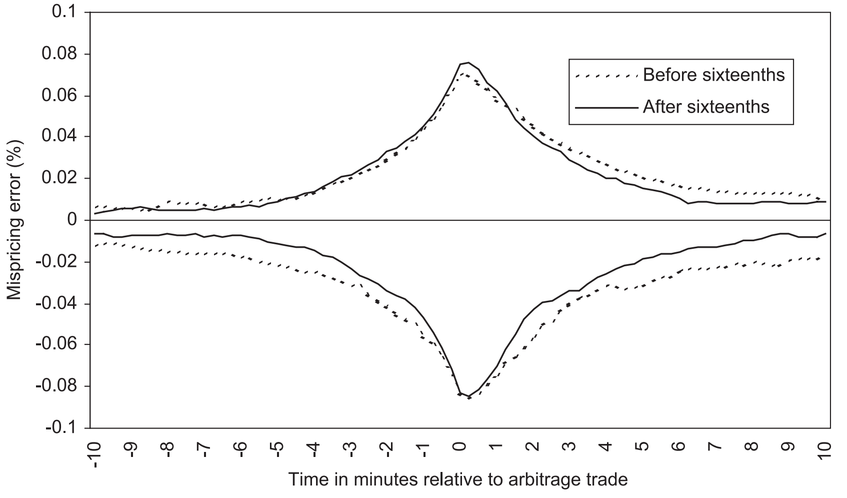

Fig. 1. Percentage market-implied MPE around reported arbitrage trades before and after the introduction of sixteenths. The figure shows the average percentage mispricing error (MPE), the difference between the futures-implied index value defined in Eq. (4) and the midpoint index defined in Eq. (2), 10 min prior and 10 min after arbitrage trades reported to the SEC. Time 0 is the time at which the arbitrage position was initiated.

in Miller et al. (1994) and Kawaller (1991). Kawaller explains that purchases and sales occur in the market with the lower price causing mean reversion. Therefore, the coefficients for mean reversion should not be considered independently but rather relative to the no-arbitrage regime. Considering the 2-min frequency, we observe that the MPE decays more quickly in the outer regimes when arbitrage is possible than it does in the no-

Table 5

AR(1) coefficient in a TAR model for the percentage MPE at various price frequencies

Frequency	Before sixteenths (3 January–23 June, 1997)			After sixteenths (24 June–23 December, 1997)		
	Buy programs	Sell programs	No arbitrage	Buy programs	Sell programs	No arbitrage
1 min	0.470 (0.0278)	0.552 (0.0325)	0.678 (0.00237)	0.393 (0.0243)	0.382 (0.0283)	0.669 (0.00231)
2 min	0.340 (0.0287)	0.435 (0.0361)	0.541 (0.00246)	0.239 (0.0236)	0.326 (0.0292)	0.558 (0.00237)
Sample size	1483	1431	163,804	2074	1741	172,711

A threshold autoregressive model of order 5, TAR(5), is estimated for the market-implied percentage mispricing error (MPE). The model also includes five lagged index returns. The data are divided into three regimes (buy programs, sell programs, and no arbitrage) based on the times the arbitrage trades were reported to the NYSE. The table reports the AR(1) coefficient for the lagged MPE and the standard error (inside parentheses). The contemporaneous MPE, the left-hand-side variable in the TAR(5) model, is the MPE one period later than the lagged MPE, which is 1 or 2 min for the 1- and 2-min frequencies, respectively. The 'market-implied' MPE is constructed such that the average difference between the log futures price and log midpoint index for each trading day is equal to zero. MPEs in percentage points are computed by dividing the difference between the futures implied index and midpoint index by the midpoint index and multiplying by 100.

arbitrage regime. Comparing the two panels, the coefficient estimate for a_1 at the 2-min frequency drops from 0.340 (0.435) to 0.239 (0.326) for the buy (sell) regime after the introduction of sixteenths.[20] Hence, the mean reversion of the MPE is faster after the introduction of sixteenths. Since the average dollar size of arbitrage trades decreased after sixteenths, one possible explanation is that more arbitrage traders are active. The average number of arbitrage trades per interval, considering only those intervals in which arbitrage trades occurred, increased significantly from 1.084 before sixteenths to 1.130 after sixteenths, with a z-statistic of 5.0.[21] The difference indicates that the number of parties engaging in index arbitrage trades increased with the decrease in transaction costs. The reduction of transaction costs may reduce the advantage enjoyed by the member firms that can internally match client orders with the arbitrage trades over the institutional investors who are more likely to need market makers for fast execution.

5. Conclusion

We find that after the introduction of sixteenths on June 24, 1997, there is a significant increase in the number of arbitrage opportunities verified by the increase in arbitrage trades, as reported to the SEC. The average dollar amount underlying each arbitrage trade and the number of shares traded for each company decrease. The average number of different stocks involved in each arbitrage trade increases. These findings are consistent with the literature that reports that transaction costs for small orders and the quoted depth both decreased after the introduction of sixteenths.

We find that the average mispricing error that triggers arbitrage is significantly smaller after sixteenths. The reduction in the mispricing error, however, is less than half the average reduction in transaction costs. Many arbitrageurs can circumvent the NYSE specialists for a substantial number of the stocks required for arbitrage. As a result, these arbitrageurs only partially benefit from the reduced spreads. We do find a slight increase in the number of arbitrageurs active at the same time, and an increase in the speed of mean reversion after the introduction of sixteenths.

Reductions in the minimum price increment reduce the effects of price discreteness and therefore reduce market friction. With the additional evidence provided in this paper, we conclude that the arbitrage link between the S&P 500 spot index and the S&P 500 futures contract has strengthened with the reduction in the minimum price increment to sixteenths of a dollar. Deviations between futures and spot prices from fair value were reduced and persisted for shorter periods of time. For future research, it will be interesting to see the impact of the further reduction in minimum price increments with the introduction of decimal pricing. During the time period of our study, if market makers decide the spread of one sixteenth is too small to be profitable, the next possible quote is one-eighth. Decimal

[20] Similar results are obtained for the cost-of-carry MPE. For the 2-min frequency, the estimate for a_1 drops from 0.365 (0.489) to 0.189 (0.382) for the buy (sell) regime after the introduction of sixteenths.

[21] We assume a multinomial distribution for the number of arbitrage trades. The 'probability' of a single arbitrage trade is 0.931 under eighths and 0.894 under sixteenths, and the 'probability' of two arbitrage trades in the same interval is 0.058 under eighths and 0.088 under sixteenths.

pricing will make it possible to quote spreads between one-eighth and one-sixteenth, potentially further reducing trading costs for arbitrageurs.

Acknowledgements

We are grateful to two anonymous referees and Richard T. Baillie (the editor) for insightful and constructive comments. We also thank Doug Foster, Ron Bewley, and Stephen Brown, participants of the 2000 Australasian Finance and Banking Conference, the 2001 Financial Management Association meeting, and seminar participants at the University of New South Wales, and Macquarie University for helpful comments. The authors thank Julia Henker and Thuy To for their excellent research assistance, and we acknowledge financial support from the University of New South Wales and the Australian Research Council. We are responsible for remaining errors.

References

Aggarwal, R., Park, Y.S., 1994. The relationship between daily U.S. and Japanese equity prices: evidence from spot versus futures markets. Journal of Banking and Finance 18, 757–773.

Balke, N.S., Fomby, T.B., 1997. Threshold cointegration. International Economic Review 38, 627–645.

Bollen, N.P.B., Whaley, R.E., 1998. Are teenies better? Journal of Portfolio Management 25, 10–24.

Brennan, M.J., Schwartz, E.S., 1990. Arbitrage in stock index-futures. Journal of Business 63, 7–31.

Chung, Y.P., 1991. A transaction data test of stock index-futures market efficiency and index arbitrage profitability. Journal of Finance 46, 1791–1809.

Dwyer Jr., G.P., Locke, P., Yu, W., 1996. Index arbitrage and nonlinear dynamics between the S&P 500 futures and cash. The Review of Financial Studies 9, 301–332.

Elton, E.J., Gruber, M.J., 1970. Marginal stockholder tax rates and the clientele effect. Review of Economics and Statistics 52, 68–74.

Engle, R.F., Granger, C.W.J., 1987. Co-integration and error correction: representation, estimation, and testing. Econometrica 55, 251–276.

Goldstein, M.A., Kavajecz, K.A., 2000. Eighths, sixteenths and market depth: changes in tick size and liquidity provisions on the NYSE. Journal of Financial Economics 56, 125–149.

Harris, L., 1997. Decimalization: a review of the arguments and evidence, working paper, University of Southern California.

Jones, C.M., Lipson, M.L., 2001. Sixteenths: direct evidence on institutional execution costs. Journal of Financial Economics 59, 253–278.

Kalay, A., 1982. The ex-dividend day behavior of stock prices: a re-examination of the clientele effect. Journal of Finance 37, 1059–1070.

Kawaller, I.G., 1991. Determining the relevant fair value(s) of S&P 500 futures: a case study approach. Journal of Futures Markets 11, 453–460.

Kawaller, I.G., Koch, P.D., Peterson, J.E., 2001. Volume and volatility surrounding quarterly redesignation of the lead S&P 500 futures contract. Journal of Futures Markets 21, 1119–1149.

Koski, J.L., 1996. A microstructure analysis of ex-dividend stock price behavior before and after the 1984 and 1986 Tax Reform Acts. Journal of Business 69, 313–338.

MacKinlay, A.C., Ramaswamy, K., 1988. Index-futures arbitrage and the behavior of stock index-futures prices. The Review of Financial Studies 1, 137–158.

Martens, M., Kofman, P., Vorst, A.C.F., 1998. A threshold error-correction model for intraday futures and index returns. Journal of Applied Econometrics 13, 245–263.

Miller, M.H., Muthuswamy, J., Whaley, R.E., 1994. Mean reversion of Standard & Poor's 500 index basis changes: arbitrage induced or statistical illusion? Journal of Finance 49, 479–513.

Neal, R., 1996. Direct tests of index arbitrage models. Journal of Financial and Quantitative Analysis 31, 541–562.

Overdahl, J., McMillan, H., 1998. An evaluation of the effects of NYSE Rule 80A on trading costs and intermarket arbitrage. Journal of Business 71, 27–53.

Ross, K., and Sofianos, G., 1998, An analysis of price volatility October 27 and 28, 1997, NYSE working paper 98-04.